Potential for a Lidar-Based, Portable, 1 km Meteorological Tower

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ABSTRACT

Lidar measurements of wind, temperature and water vapor, using a variety of techniques that rely on the detection and analysis of laser light backscattered from the atmosphere, allow data to be obtained that are similar to those hypothetically available from a meteorologically instrumented tower extending to 1 km altitude (or more). This paper reviews these various recent accomplishments in lidar instrumentation without attempting historical completeness. Based on criteria of 1) altitude resolution to 50 m, 2) tower-like measurement geometry, 3) hardware commonality between techniques and 4) daytime as well as nighttime operation, the intercomparison results in recommended techniques to be combined for a compact, mobile lidar "tower." For horizontal wind, recommendations include pulsed time-of-flight lidar; for vertical wind, pulsed direct Doppler lidar at visible or shorter wavelengths; for temperature, Cabannes-scattering linewidth or rotational Raman band shape; and for water vapor, vibrational Raman scattering. Although further development of some of these techniques is needed to achieve the desired range and resolution, results in the literature support the conclusion that a lidar tower is a feasible concept for meteorological measurements under conditions allowing direct optical propagation.

1. Emerging lidar remote sensing technology

Research in a number of laboratories on lidar (optical radar) measurement of meteorological variables leads to an expectation that wind, temperature and humidity profiles could be measured to a height of at least 1 km with 50 m or better height resolution from a compact, ground-based lidar system. For some boundary layer applications, a multipurpose meteorological lidar could supplement or replace fixed meteorological towers.

My purpose in this review is to collect results of applicable optical remote sensing research and apply these concepts to the measurement of boundary layer meteorological parameters. On the basis of previous work, it is possible to project capabilities of a specially-designed lidar system and critically assess alternative approaches. By using this special issue of the *Journal of Climate and Applied Meteorology* to reach a wide audience of meteorologists interested in instrumentation, I intend to make available to the user community lidar results that have appeared in more specialized articles, often in the optical literature, or in reference to particular applications.

Development of a lidar "met tower" is in its early stages. By exposing the meteorological community to the measurement concepts and achievements now, we hope to encourage boundary layer and mesoscale meteorologists to make suggestions that will shape further development of the lidar tower in ways that would be most useful for field measurements. For example, the tradeoffs between altitude resolution and velocity resolution, and between measurement time and instrument size, are more easily adjusted before rather than after lidar hardware design.

The notion of a portable, 1 km meteorological "tower" is a framework that can connect the emerging lidar measurement capabilities for wind, temperature and humidity with various experimental needs. Two of the possible fields of application are pollution dispersal research and mesoscale dynamics. In these fields the existence of profile data for wind, temperature and humidity to 1 km, continuous or near-continuous in time, should allow researchers to obtain data previously considered inaccessible or impractical to obtain. The lidar tower can be located easily with respect to a topographic feature and even moved if the synoptic-scale situation changes. Remote sensing is not subject to the aerodynamic loads or air navigation interference associated with kite or tethered-balloon sounders. Under some conditions data can be taken above 1 km, which should be helpful, for example, in studying the structure of gust fronts and similar features. This article will have served its purpose if it stimulates the design of new or expanded parts of field research programs to which meteorological lidar can contribute.

A meteorological lidar operates by measuring the spectral or temporal characteristics of laser light backscattered from molecules and particulates in the atmosphere. The range (altitude) resolution limit for a pulsed, vertically-pointing system depends on the transmitter pulselength and is approximately 50 m for a 300 ns pulse. Because velocity resolution and range resolution are coupled by means of wavelength as discussed later and because temperature and humidity measurements rely on molecular scattering, the lidar tower operates at visible or near-ultraviolet wavelengths. Use of this spectral region raises the question of eye safety, even though the transmitted pulse energy for a portable system is only a few hundred millijoules. The safety issue is handled by noting that the lidar elevation angle is vertical for this application (no hazard to people on the ground) and by using a small, boresighted safety radar (nonscanning) to hold open a shutter if a logic circuit determines that the radar is operating and that the radar return is below a target threshold. The safety radar can be a simple, low-powered unit capable of detecting a light aircraft at a few kilometers range or closer.

Compared with the remote sensing field as a whole, including lidar, the portable met-tower lidar concept emphasizes the short-range, high-resolution, fine-scale part of the field. Thus the lidar tower complements but neither competes with nor replaces longer range techniques, such as various kinds of radar, microwave and infrared radiometry, and long-range lidar. In addition, the short-wavelength lidar is unable to penetrate dense clouds, so it yields in favor of radar wavelengths for cloud interior applications.

2. Wind measurement capability of a lidar tower

Particulates in the atmospheric aerosol move with the wind and serve as flow markers for optical wind sensors. Laser light backscattered from a particle will be Doppler shifted in frequency if the particle has a velocity component along the lidar line of sight. On the other hand, a particle moving transverse to the line of sight can scatter from two separated beams with a time delay that depends on the transverse velocity component and beam spacing. These two different mechanisms are useful for different wind components as outlined below.

a. Horizontal wind

With respect to a vertically-pointing lidar tower, horizontal wind represents velocity components transverse to the optic axis. Early work on transverse velocity measurement (Bourke and Brown, 1971) used intersecting beams to project a fringe pattern in the sensing volume by means of optical interference, but both theory (Lading, 1976) and recent practice (Lading *et al.*, 1978; Bartlett and She, 1977; She and Kelley, 1982) indicate the superiority of a time-of-flight technique for the measurement of atmospheric velocity components perpendicular to the lidar line of sight.

In the time-of-flight method, the transmitted energy is split into two beams that are focused at the height of interest. The focal volumes must be small (near the diffraction limit) and closely spaced for best operation. Fig. 1 shows a schematic diagram of the geometry where both of the transmit beams and the receiver share a common telescope (transceiver). An airborne particulate, part of the atmospheric aerosol, that passes through both focal volumes will give a double-pulse backscattered signal. The transverse velocity component V_t is determined from the time

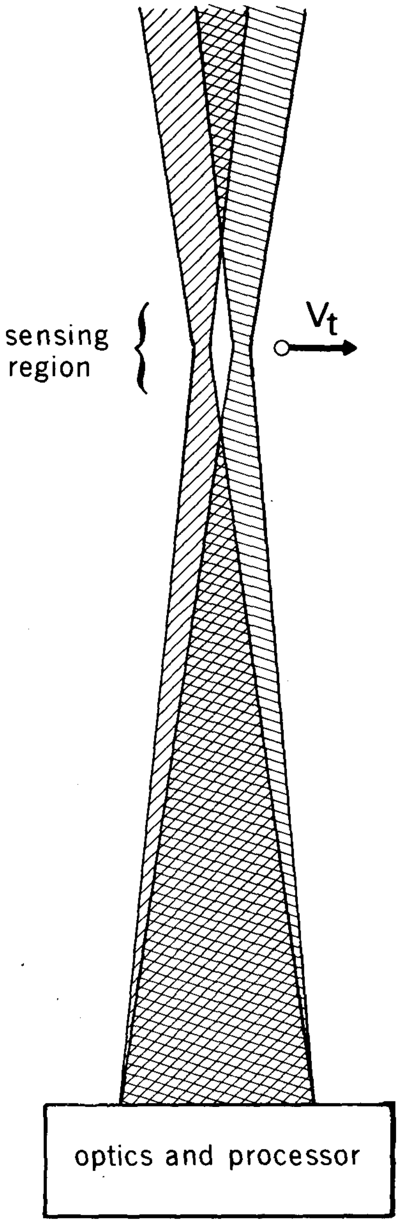

FIG. 1. Schematic diagram (side view) of the geometry for measurement of horizontal wind with a lidar-based meteorological "tower." V_t is the atmospheric velocity component transverse to the optic axis in the plane of the two beams. Both of the transmit beams and the corresponding congruent receive beams use the same telescope aperture.

delay between the two pulses and the spacing between the sample volumes. Each aerosol particle that is large enough to produce a measurable signal and that passes through both focal volumes gives an independent measure of V_t. Both components of the horizontal wind can be measured either by 1) using three beams in two orthogonal planes or by 2) rotating the plane of two beams so that the conditional probability of a pulse in the second beam, given a pulse in the first, is a maximum, thus giving the magnitude and azimuth of the horizontal velocity. The second method is preferred because it results in a maximum data rate for two-pulse signals. The rotation can be done with a servo system, although this is not as responsive as a wind vane.

Practical time-of-flight lidar systems working at visible wavelengths have already demonstrated a useful range of 100 m (She and Kelley, 1982) and functioned in daylight conditions (Lading *et al.*, 1978) at their present stage of development. Temporal resolution is on the order of milliseconds per measurement, depending on the aerosol particle density and range. With a continuous wave (cw) system and a few-centimeter transceiver aperture, the spatial resolution is a few millimeters transverse to the line of sight and approximately 10 m along the beam at an altitude of 100 m. The velocity measurement accuracy is controlled by the uncertainty in the separation of the two beams. This separation can be determined easily to ±1% in the absence of refractive index homogeneities so that the accuracy in wind estimate depends primarily on fluctuations in the measurements caused by turbulence and differential refractive beam wander.

Additional developments are possible. Although most work to date has used a cw transmitter, a pulsed transmitter with a time-gated receiver has a number of advantages such as 1) improvement in vertical resolution at ranges beyond 100 m where depth of focus, which increases as the square of the range, becomes large, 2) reduction in background light interference because of the higher peak power of a pulsed transmitter compared with a cw source, and 3) reduction of interference from instrumentally-scattered light in the transceiver because of the time separation between transmitted and received signals. Armstrong *et al.* (1976) used a pulsed ultraviolet lidar for transit-time measurements, although their beam separation and beam diameters were much larger than more recent practice; they did not use a transceiver. The transceiver has the advantages over separate transmit and receive telescopes of easier beam alignment, optimum matching of transmitter and receiver sensing volume dimensions, and compactness.

Time-of-flight velocity measurements are a logical way to make horizontal wind measurements from a lidar tower, but the technique has room for further development. The effect of atmospheric refractive index inhomogeneities for altitudes (ranges) beyond 100 m is not completely documented. It is possible that operation in the infrared (Lading *et al.*, 1980), rather than the visible, will give more consistent results at higher altitudes where the sample volumes are larger and include a larger number of particles, because the infrared backscatter is more sensitive to fewer, larger particles (Post, 1978) than visible backscatter is. Alternative methods for horizontal wind measurements are discussed in Section 2c.

b. *Vertical wind*

Lidar measurement of vertical wind with a vertically-pointing lidar utilizes a direct Doppler approach as sketched in Fig. 2. Light backscattered from particulates in the atmosphere that are moving with a vertical velocity component will be Doppler shifted. This shift is approximately 4.1 MHz per 1 m s^{-1} velocity for visible light (488 nm wavelength) and 188 kHz per 1 m s^{-1} for infrared (10.6 μm). The lidar geometry for measurement of the vertical wind and that for measurement of the horizontal wind are compatible with each other, as can be seen by comparing Fig. 1 with Fig. 2.

Practical measurements of vertical atmospheric velocity have been reported by Benedetti-Michelangeli *et al.* (1972, 1974), using a visible-wavelength pulsed lidar, and by Schwiesow and Cupp (1981) using an infrared-wavelength cw lidar. In the former case the Doppler shift was measured with a Fabry-Perot interferometer (temporally incoherent processing) and in the latter case with an optical heterodyning technique (temporally coherent processing). For the visible lidar, results have been obtained primarily at night to a range of approximately 1 km with only 300 m range resolution, but with a few-centimeter resolution transverse to the beam. With a scanning interferometer, Benedetti-Michelangeli *et al.* (1974) used 3 s to produce one velocity estimate at many range gates in parallel. Their measurement accuracy was ±0.3 m s^{-1} for a single measurement and was estimated to be ±0.03 m s^{-1} for an average of 100 measurements. In contrast, the infrared lidar used by Schwiesow and Cupp (1981) with a 30 cm transceiver operates routinely in daylight, but to a range of only a few hundred meters with 12 m range resolution at 100 m, increasing with the square of the range. A velocity spectrum at a single height was produced every 5 s with the data processing used. The measurement uncertainty is ±0.25 m s^{-1} for a single measurement, but could be as small as ±0.05 m s^{-1} with slight optical redesign.

Direct Doppler lidar measurements of vertical velocity using two different spectral regions are workable now, but refinements in the hardware can be made. One area for further research concerns the possibility of heterodyne processing in the visible in

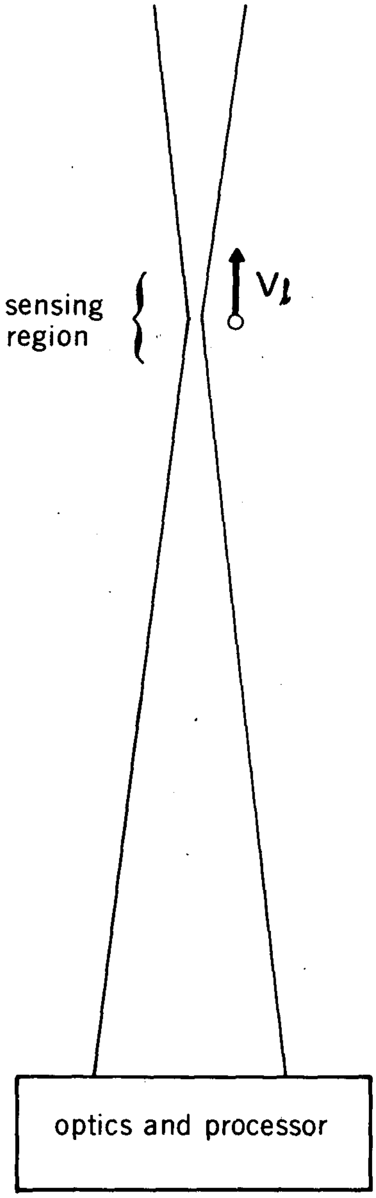

FIG. 2. Schematic diagram (side view) of the geometry for measurement of the vertical wind with a lidar-based meteorological "tower." V_l is the atmospheric velocity component along the optic axis (longitudinal or radial). The transmit and receive beams are congruent to each other and use the same telescope aperture.

the presence of refractive index inhomogeneities. Improvement in altitude resolution by short-pulse lidars is limited by the transmitter frequency broadening caused by pulsing. A Gaussian pulse of width τ [s] in the time domain transforms to a Gaussian spectrum $1/\tau$ [Hz] wide in the frequency domain. The range resolution Δz from a pulse τ wide and the velocity resolution Δv corresponding to a frequency spectrum $1/\tau$ wide are related by

$$\Delta z \Delta v = c\lambda/4,$$

where c is the speed of light and λ the lidar wavelength. At a given wavelength, a reduction in Δz requires an increase in Δv. This pulselength limitation on the Doppler lidar does not apply to the time-of-flight technique, however. A 300 ns pulse, for example, which gives a 50 m lidar range resolution, results in a transmitter frequency broadening of ~3 MHz. Although Doppler shifts smaller than the transmitter bandwidth can be measured if there is a sufficiently large signal-to-noise ratio, a practical limit on the accuracy of Doppler shift determination is approximately the transmitter bandwidth. As a result, 50 m range resolution by pulsing would cause approximately a 0.7 m s^{-1} uncertainty in vertical velocity measured with a visible-wavelength lidar and would be completely unacceptable with an infrared lidar.

c. Relation to other techniques

For measurement of transverse (horizontal) velocity, one can consider the coherent differential Doppler (Schwiesow *et al.*, 1977) or hybrid dual-frequency Doppler-lidar (Eberhard and Schotland, 1980) techniques. In contrast to the time-of-flight approach, which uses a single transmitter aperture and two sample volumes, these two alternative techniques use transmitter beams from two separate apertures focused to a common point in space. Because the differential Doppler and hybrid dual-frequency Doppler techniques are less highly developed than the time-of-flight method and because of the problems of alignment and size with two separate transmitter apertures, I have chosen the time-of-flight method for transverse velocity sensing with the lidar meteorological tower.

By tracking the motion of patterns in backscatter inhomogeneity it is possible to determine wind profiles in some average sense (Eloranta *et al.*, 1975; Sroga *et al.*, 1980). Although cross correlation of backscatter patterns produces useful wind profiles of the horizontal wind at over 2 km range, the time (~5 min average) and space (250–1000 m resolution) scales of the operation are too large for many tower-scale studies. In addition, the vertical component of velocity is inaccessible to the technique and measurements are made more than 1 km away from the lidar location.

The outline of a lidar meteorological tower includes the use of a direct Doppler approach for radial wind measurement in the vertical direction. By employing a scan for a velocity-azimuth display (VAD or conical scan) at some elevation angle near 45° it is possible to infer all three components of the wind averaged over the region of the scan, from radial velocity measurements alone. The region of the scan is an inverted cone with a cross-sectional radius at any altitude equal to the altitude over the tangent of the elevation angle. I have *not* suggested a VAD scan for the lidar tower for a number of reasons. First, analysis of VAD results requires assumptions such as strict horizontal homogeneity or linear variation with no vertical velocity (Waldteufel and Corbin, 1979). These assumptions are not valid for a large number of important boundary layer research topics, such as flow in complex terrain, wind in the urban environment, building wake studies, wind turbine research, and flow near storms (e.g., DiMarzio *et al.*, 1979). Any horizontal shear will introduce error into velocity component inferences. Second, the time response of VAD wind measurements is limited to the scale of the diameter of the scanned cone divided by the mean crosswind at the altitude of interest. At 1 km altitude and 45° elevation angle, for example, the time response of VAD velocity inferences would be a few hundred seconds for winds below 10 m s^{-1}. Finally, even in homogeneous terrain the lower boundary layer is rarely horizontally homogeneous and stationary in time. Any departures from a fixed wind speed and direction introduce measurement errors that have not been fully analyzed anywhere in the literature to our knowledge.

Pulsed, coherent, direct-Doppler measurements of the radial wind using a large infrared lidar (Post *et al.*, 1981) are being used for some applications. Such a lidar is not useful for lidar tower applications because its range resolution (300 m and greater) is on too large a scale for extended tower-like measurements, it suffers from the limitations of a VAD scan for three-component measurements, and its minimum sensing range is 1.5 km.

In addition to the resolution advantage of visible-wavelength wind-sensing lidars over infrared-wavelength lidars, aerosol scattering in the visible is stronger than in the infrared. One recent experiment (Schwiesow *et al.*, 1981) showed the backscatter cross section at 694 nm wavelength to be a factor of 420–1140 times larger (depending on altitude) than the cross section at 10.6 μm. Even though quantum noise limitations favor the infrared over the visible by a factor of approximately 20 for equal transmitter powers, the larger cross-section factor dominates the aerosol-scattering signal-to-noise ratio comparison for direct Doppler (but not necessarily for time-of-flight sensing).

Comparing other techniques, I have chosen to use time-of-flight lidar for horizontal wind measurements over fringe-type systems because of better demonstrated performance in the field and the instrumental simplicity of a single telescope aperture. The time-of-flight approach has the advantage over the conical scan of better temporal resolution, smaller (more tower-like) sample volume, and freedom from necessary assumptions on horizontal homogeneity. For vertical wind measurements I have chosen a direct (radial) Doppler approach, probably working at visible wavelengths because, in the infrared, cw systems of 30 cm coherent aperture, for example, have poor height resolution at 500 m altitude and no resolution beyond, and pulsed systems have either inadequate range resolution, inadequate velocity resolution, or both inadequacies for meteorological tower applications. The combined time-of-flight and direct-Doppler techniques have the advantage over backscatter pattern correlation of better temporal and spatial resolution, simpler processing, and sensing at the tower location. On the other hand, pattern correlation can give a two-dimensional spatial pattern, rather than the tower-like profile of the system we have chosen. Comparisons of one method to another made here are only valid for the meteorological tower application. For other purposes, approaches other than time-of-flight and vertical, direct Doppler may be most promising. For example, for the wind shear problem on an airport approach path, a cw infrared Doppler may be most useful; for studies of convective plume organization, a pattern correlation measurement may be indicated.

Non-optical remote sensors for wind are beyond the scope of detailed comparison for this paper, but some general comments may help put the lidar approach in perspective. Lidar wind measurements rely on aerosol particles in the range of 0.1–5 μm radius as flow markers. Aerosol particles are conservative tracers in the sense that they are not generated internally by the flow. Acoustic and radar wind sensors rely on scattering from nonconservative refractive index inhomogeneities, particularly temperature fluctuations. In general, aerosol particle tracers are distributed more uniformly in the lower atmosphere than temperature inhomogeneities are, so the lidar has a spatial sampling advantage over remote sensors that rely on inhomogeneities that may cluster near shears and/or inversions, particularly on a tower measurement scale.

3. Temperature measurement with a lidar tower

Temperature measurements based on molecular backscatter are consistent with the philosophy and geometry (Fig. 2) of the lidar tower. Two different scattering mechanisms, rotational Raman and Cabannes (Young, 1981), are useful for boundary layer profiling.

a. Rotational Raman scattering

The rotational Raman-scattering spectrum of atmospheric molecules is temperature dependent because the shape of the envelope of the many spectral lines corresponding to transitions between rotational energy levels in the ground state manifold reflects the temperature-dependent populations of the energy levels. By measuring the ratio between two parts of the rotational Raman band, temperature can be inferred.

Cooney (1972) and coworkers (Gill *et al.,* 1979) have made measurements of temperature profiles to 2 km altitude with an average departure from a radiosonde profile of ±0.85°C. They used a ruby laser transmitter at 694 nm wavelength and interference filters to select spectral regions. In the reported experiment, the spatial resolution was 75 m and a profile was measured in 4 min. One limitation on the present temperature-profiling lidar is that the measurements reported were made at night to avoid interference from sky background.

One possible improvement in the lidar is to change to a coaxial optical geometry to allow data to be taken both above and below 1 km with each transmitter pulse. Another improvement would be to use a transmitter wavelength in the ultraviolet to reduce sky background interference. The fact that the Raman-scattering cross section is approximately 0.02 times the Cabannes, and that only a part of the total rotational Raman band is used, is a fundamental limitation of the technique.

b. Cabannes scattering

Molecules in thermal equilibrium move with a translational velocity distribution described by Maxwell-Boltzmann statistics. Light backscattered from the moving molecules will be spectrally broadened by a direct Doppler shift. Thus the Cabannes-scattering (often given the more inclusive name Rayleigh scattering) linewidth is dependent on temperature because the translational velocity distribution of the molecules depends on temperature. By measuring the scattering linewidth as a function of altitude, one determines a temperature profile.

Fiocco *et al.* (1971) and Benedetti-Michelangeli and Fiocco (1974) used the linewidth technique to measure a profile to approximately 5 km altitude with an accuracy estimated to be a few degrees Celsius. They used an argon laser transmitter at 488 nm wavelength and a chopper to pulse the transmitter output, resulting in a range gate of a few hundred meters. With a scanning Fabry-Perot interferometer it took approximately 1 h to obtain a full spectrum and a single temperature point. As in the case of the rotational Raman experiments, measurements were made at night to reduce background light.

Improvements in technology since 1971 allow one to estimate the performance of a Cabannes-scattering lidar for temperature profiling based on more powerful lasers and parallel-processing spectral analysis. Schwiesow and Lading (1981) have calculated that a lidar at 488 nm wavelength and modest laser power and telescope aperture can measure temperature at 5 km with 50 m altitude resolution to ±1 K in 75 s integration time under daylight conditions. Measurements at lower altitudes can be made more rapidly.

Compared with rotational Raman scattering, the narrower-bandwidth technique that is based on Cabannes linewidth has the advantage of greater backscatter cross-section and the disadvantage of requiring a narrow-bandwidth transmitter. Both molecular scattering techniques are conceptually direct and can be clearly analyzed. The ability to make daytime temperature measurements with the linewidth technique is a natural consequence of the use of a narrow-bandwidth laser transmitter because appropriate lasers operate in single longitudinal and transverse modes, thus making near-diffraction-limited operation an attractive way to reduce the amount of background light detected.

c. Relation to other techniques

Differential absorption is a technique for probing the population of ground state levels in atmospheric molecules by means of changes in the absorption spectra of the molecules (Mason, 1975). One particular example measures the difference in return signal between the energy backscattered from transmitted energy at two different spectral lines, which are chosen so that one line is at an absorption of the molecule of interest and the other line is spectrally close but at an absorption-free region of the spectrum. The absorption is a measure of temperature along the absorbing path because the absorption depends on the ground-state population distribution (assuming the molecular species is well mixed in the atmosphere), which in turn depends on temperature.

Choosing an appropriate transmitter laser is difficult (Barton and Le Marshall, 1979), but differential absorption measurements have been made with the help of a retroreflector and two dye lasers (Kalshoven *et al.,* 1981). This measurement was not a lidar measurement because the path was not single ended, but lidar measurements should be possible when aerosol backscatter, rather than a retroreflector, is used as a target. The experiment of Kalshoven *et al.* measured average temperature over a 1 km path to ±1°C using integration times of less than 1 min with approximately 50 mW cw laser power in each beam.

Range-resolved differential absorption measurements are required to determine a temperature profile rather than a line average. Range-resolved differences are inherently difficult because one is dealing with small differences in comparatively large absorption values at two different ranges. For the absorption differences to be sufficiently large to be above noise, substantial range differences must be used. The goal of one program (not yet achieved) (Kalshoven *et al.,* 1981) is a range resolution of only 2 km. This is not appropriate for an extended boundary layer tower.

Another method for inferring temperature is to measure the molecular density profile by means of the profile of vibrational Raman intensity of N_2. Strauch *et al.* (1971) determined relative temperature at a single point with a few degrees uncertainty in 3 s of integration time. Although the measurements were at a range of 30 m and a resolution of 5 m in altitude, the authors estimate that lidar equipment available in 1971 could measure temperature profiles to several kilometers. One complication in the density profile approach is that a statistical model of the pressure profile (or height integration of density) is required to infer temperature. On the other hand, density data are directly available in a lidar mode without dependence on aerosol targets or signal differences.

I have chosen to use molecular scatter, either rotational Raman or Cabannes, for the lidar tower over alternative techniques. The chosen approach has the advantages over differential absorption of better height resolution, freedom from restrictions on and need for control of laser wavelength, field demonstration in a lidar mode, and simple, direct analysis. Temperature measurement by temperature-dependent spectroscopy has the advantages over the density profile of using intensity ratios rather than calibrated intensity and being free of the need for auxiliary data such as pressure and optical attenuation profiles.

Passive remote sensors for temperature profiling are beyond the scope of detailed comparison for this paper. In general, however, the radiometric sensors, whether operating in the infrared or microwave spectral regions, do not provide the vertical resolution required for tower-like measurements, although the radiometric profilers have much greater maximum altitude capability than the lidar. Radiometric and lidar temperature profilers complement each other in this sense.

4. Water vapor measurement by lidar

a. *Vibrational Raman spectra*

The energy backscattered from a molecular atmosphere is proportional to the molecular density. Vibrational Raman spectra are shifted from the exciting wavelength by an amount that is characteristic of the molecule (and the transition), so that the Raman-scattered signal from one molecular species can be differentiated from the signal that is scattered by a different species. By measuring the ratio of energy Raman-scattered by H_2O to that Raman-scattered by N_2, one determines the water vapor mixing ratio. If the atmospheric transmission is approximately independent of wavelength, then the signal ratio at H_2O-to-N_2 Raman lines gives the mixing ratio independent of lidar system variables such as laser power and alignment, and independent of atmospheric attenuation and refractive index inhomogeneities. Once the mixing ratio is known, the absolute amount of water vapor can be determined with the help of a measured or modeled N_2 density profile.

A number of atmospheric water vapor measurements have been made using vibrational Raman spectra. Among those experiments are those of Melfi *et al.* (1969), Cooney (1970), Strauch *et al.* (1972) and Pourny *et al.* (1979). Recent experiments measured the water vapor profile to 1800 m altitude with 30 m vertical resolution and a 15% uncertainty in the mixing ratio at 1000 m. To achieve these results, Pourny *et al.* used 30 shots of a 0.2 J frequency-doubled ruby laser at 347 nm and a 25 cm aperture collecting telescope.

Although these water vapor results are useful, most experiments using the vibrational Raman spectrum of water vapor have been limited to night operation because of skylight interference in the daytime. One solution to the background interference problem is to operate further into the ultraviolet, as analyzed by Cooney *et al.* (1980). Renaut *et al.* (1980) made daytime measurements of the water vapor mixing ratio to 1000 m altitude with 30 m vertical resolution and a 10% uncertainty in the mixing ratio at 500 m. The experiment needed 50 shots of a quadrupled Nd:YAG laser (in ~30 min), operating with 100 mJ per pulse at 266 nm wavelength, and a 60 cm telescope aperture. One complication in operating at these wavelengths is the correction for differential absorption at the N_2 and H_2O Raman shifts. Renaut *et al.* estimate improved daytime performance based on a better, but available, laser system than the one used in the experiment.

Another approach to reducing background light is to reduce the field of view of the lidar to nearly the diffraction limit (Schwiesow and Lading, 1981), while operating at convenient wavelengths in or near the visible region. Reducing the field of view requires a common telescope for transmitter and receiver rather than the side-by-side parallel-axis configuration usually used for short-wavelength lidars. Although the transceiver configuration (congruent transmit and receive telescopes) has not been used in the visible, to our knowledge, it has been highly successful in the infrared, especially with coherent, heterodyne Doppler lidars (e.g., Schwiesow and Cupp, 1981). The proper position and size for the receiver field stop tends to protect the detector from overload at close ranges.

Although daytime measurements of water vapor profiles based on Raman scattering have already been successfully demonstrated, there appears to be potential for near-term improvement in laser power and optical configuration.

b. *Differential absorption measurements*

The differential absorption technique, outlined in a previous section, can be used to make water vapor partial-pressure measurements because the absorption of optical energy at a wavelength where the molecule of interest absorbs depends on the amount of absorbing material in the beam. By comparing the return at two different wavelengths, one on and one off the absorption line, a measure of total molecular absorption can be made, and by determining the difference in absorption to two different ranges, an estimate of molecular concentration in the region between the two range points can be made, thus providing a concentration profile.

Werner and Herrmann (1981) report daytime results on water vapor partial-pressure profiles up to an altitude of 1500 m with a 100 m range resolution. Their well-developed system uses two independent ruby lasers with 1 J output pulse energy, one tuned to a water vapor absorption line and one tuned off the line. With a 40 cm telescope for the absorbed wavelength, approximately 20 pulses are averaged over 30 min to achieve 1 mb (~10%) uncertainty for each resolution element.

Alternative approaches are possible. Browell *et al.* (1980) suggest the use of laser-pumped dye lasers, but the wavelength stabilization problem is at least as difficult as that for the ruby lasers. Werner and Herrmann (1981) recommend the use of smaller, more rapidly pulsed ruby lasers as one way of improving existing instrumentation.

c. *Comparison of techniques for water vapor profiling*

In contrast to the situation for wind and temperature, where one measurement technique appears to have definite advantages in the lidar meteorological tower application, neither vibrational Raman scattering nor differential absorption has a clear relative advantage for water vapor profiling. The demonstrated performance of both methods is similar to that of the other, and instrumental complexities, though different in nature, are similar in degree. Differential absorption requires careful control of laser wavelengths to an absolute standard, whereas any wavelength is suitable for Raman scattering. On the other hand, optical elements for the ultraviolet, as used for daytime Raman work, are more difficult to use than elements for the red or near-infrared differential absorption.

To make a definite outline of the lidar tower, I choose Raman scattering for water vapor profile measurement, primarily because the molecular scattering approach is consistent with the preferred technique for temperature profiling. In addition, the Raman technique has given better altitude resolution than differential absorption has, and it does not have the limitation of the smaller difference of large numbers as the height resolution element becomes smaller. Achieving an adequate daytime signal-to-noise ratio with the inherently weak Raman scattering will continue to be a challenge, however. Development of near diffraction-limited lidar optics for visible and shorter wavelengths should help reduce sky background.

5. Further development of the lidar meteorological tower

The results of a number of separate experiments on lidar measurements of the profiles of atmospheric wind, temperature and water vapor show that it is feasible for a lidar-based system to provide data similar to that provided by an instrumented meteorological tower. Compared with physical towers, a lidar tower would provide portability to various experimental sites and measurements to 1500 m altitude or higher. On the other hand, a lidar tower may be less suited than a physical tower to continuous monitoring for periods of many months because of laser operating costs.

a. *Common features of the measurement techniques*

Lidar methods for measuring wind from aerosol backscatter and for measuring temperature and water vapor with molecular backscatter all use single-ended devices that provide range-resolved data along the line of sight. The data represent spatial averages over the sensing volume, which is a vertical cyclinder ~50 m high and a few centimeters in diameter, or less, depending on altitude (range).

Because they rely on optical transmission, lidar sensors will work to approximately the visual ceiling and not far into dense clouds. It is not likely that the lidar tower will be useful as an unattended measurement system within the next few years because present laser technology requires an operator to check mirror alignment.

Lidars for wind, temperature and water vapor can all use a common transceiver with a single primary mirror of 30–50 cm aperture, which need not have a scanning mount. A common, pulsed transmitter laser is also appropriate for all types of measurements. Such a laser must be either single transverse mode to operate in the visible, or it must operate in the ultraviolet at wavelengths shorter than approximately 300 nm to allow reduction in daytime background interference. For Cabannes scattering (temperature) and direct Doppler (vertical wind), the laser must operate on a single longitudinal cavity mode in order to have a sufficiently narrow instantaneous bandwidth, but the laser wavelength does not need to be controlled.

The first prototype of the lidar tower will operate in a time-shared mode for each type of measurement to reduce laser and transceiver costs, but a separate detector package is appropriate for each technique. Probably only one altitude resolution element at a time can be measured for horizontal wind, even with a pulsed laser, because the two beams for the time-of-flight determination should be focused at the sample volume. Further research on the effective depth of field for the measurement may reduce the limitation on multiple range gates for each pulse.

b. Other capabilities of a lidar tower

In addition to profiles of wind, temperature and water vapor, the lidar can easily provide profiles of aerosol backscatter, which has been the primary variable measured by most lidars. From the backscatter profile, one can infer the height of the mixed layer, the amount of pollutant trapping, and other qualitative information about the atmosphere.

The high spectral resolution needed to analyze Cabannes scattering allows one to separate molecular from aerosol backscatter (Fiocco *et al.*, 1971). In addition to a self-calibrating measure of aerosol backscatter (the aerosol to molecular ratio), the molecular backscatter profile together with a measured or modeled density profile allows one to determine the optical attenuation profile. Either vibrational or rotational Raman scattering can also be used to produce a molecular scattering signal for attenuation profiling.

c. Suggestions from the meteorological community

The feasibility of individual measurements that together make up a lidar-based meteorological "tower" has been demonstrated by various researchers. Additional development on each of the techniques is possible, as outlined in the measurement sections of this review, and a lidar system using various techniques with a common laser, transceiver, and other parts is yet to be developed.

Suggestions from meteorologists interested in the boundary layer can be very effective at this stage in the development of the lidar tower, before choices of laser, detector type and measurement technique are made. For example, is 50 m altitude resolution adequate for many important applications, can the resolution be relaxed to 100 m (putting differential absorption for water vapor in a stronger position), or should the resolution be tightened to 25 m (making a straight flashlamp-pumped dye laser inadequate)? Is an altitude capability of 1200–1500 m adequate, or should funds be committed for a larger transceiver to increase range? Is water vapor concentration uncertainty of ±1 mb appropriate for interesting boundary layer studies? How long an averaging time is possible for various applications?

Selected techniques for lidar measurement of meteorological variables exhibit enough commonality that a combined-capability lidar system is possible. Making tower-like measurements to a height of over 1 km is a goal to focus and define lidar measurement results for wind, temperature, water vapor and aerosol backscatter. The time is right to select promising techniques for a lidar tower (and the research applications it represents) and to undertake development of a lidar system that acts as a mobile, 1 km meteorological tower.

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